response, and is shown on FIG. 8 as a function of radial distance from the center of the array and of the source frequency, along the x=0 (or y=0) axis. Most of the normalized E_r response is contained within r≦1300 meters, and has a maximum value of approximately 33% at r=0 at the lowest survey frequency (f=0.005 Hz). The large normalized E_r value at r=1500 meters is a local effect of the inner radial electrode.

The benefits provided by this invention include at least the following two. The first benefit is cost and cycle-time reduction in hydrocarbon exploration, development, and production activities, including reducing exploration drill-well risk, improving discovered-undeveloped reservoir delineation and assessment, and improving reservoir monitoring and depletion. The second benefit is improved business capture of new exploration ventures and field commercializations by offering unique, proprietary reservoir properties estimation technology.

It should be understood that the invention is not to be unduly limited to the foregoing which has been set forth for illustrative purposes. Various modifications and alternatives will be apparent to those skilled in the art without departing from the true scope of the invention, as defined in the following claims.

I claim:

1. A method for surface estimation of a resistivity depth image of a subsurface geologic formation, comprising the steps of:

determining the location of and at least one average earth resistivity for the vicinity of the subsurface geologic formation using geological and geophysical data from the vicinity of the subsurface geologic formation;

determining dimensions and probing frequency for an electromagnetic source to substantially maximize transmitted vertical and horizontal electric currents at the subsurface geologic formation using the location and the at least one average earth resistivity;

activating the electromagnetic source at or near the surface of the earth, approximately centered above the subsurface geologic formation;

measuring a plurality of components of electromagnetic response with a receiver array;

determining one or more geometrical and electrical parameter constraints, using the geological and geophysical data; and

processing the electromagnetic response using the geometrical and electrical parameter constraints to produce the resistivity depth image.

2. The method of claim 1, further comprising the step of:

combining the resistivity depth image with the geological and geophysical data to estimate one or more properties of the subsurface geological formation.

3. The method of claim 1, wherein the step of determining dimensions and probing frequency is accomplished by numerically solving the uninsulated buried low-frequency electromagnetic antenna problem.

4. The method of claim 1, wherein the electromagnetic source comprises

two continuously grounded circular electrodes positioned in concentric circles.

5. The method of claim 4, wherein each circular electrode comprises one or more electrically uninsulated conductors.

6. The method of claim 4, further comprising:

a third circular electrode positioned concentric with the two circular electrodes.

7. The method of claim 6, wherein the third circular electrode comprises one or more electrically insulated conductors.

8. The method of claim 1, wherein the electromagnetic source comprises six or more grounded linear radial electrodes of equal lengths placed along radii separated by equal angles, whose radial projections intersect at a common central point.

9. The method of claim 8, wherein the radial electrodes are continuously grounded along their entire length.

10. The method of claim 8, wherein the radial electrodes are continuously grounded only within a distance less than one half of the length of the radial electrode from each end.

11. The method of claim 1, wherein the subsurface geologic formation is located onshore.

12. The method of claim 1, wherein the subsurface geologic formation is located offshore and the surface of the earth is the seafloor.

13. The method of claim 1, wherein the receiver array is positioned on a grid.

14. The method of claim 1, wherein the receiver array is positioned as a linear array.

15. The method of claim 1, wherein the receiver array is positioned as a swath array.

16. The method of claim 1, wherein the step of processing the electromagnetic response further comprises:

verifying the at least one average earth resistivity using the plurality of components of electromagnetic response measured with the receiver array.

17. The method of claim 1, wherein the step of processing the electromagnetic response further comprises:

applying 3-D wave-equation data processing to the electromagnetic response.

18. The method of claim 1, wherein the step of processing the electromagnetic response further comprises data noise suppression, source deconvolution, and model-guided inversion.

19. The method of claim 7, wherein the steps of activating the electromagnetic source and measuring the plurality of components of electromagnetic response further comprises:

measuring a first electromagnetic response without activating the electromagnetic source;

measuring a second electromagnetic response while activating only the third circular electrode; and

measuring a third electromagnetic response while activating only the two continuously grounded circular electrodes.

20. The method of claim 19, wherein the step of processing the electromagnetic response further comprises:

merging the first and second electromagnetic responses to produce a fourth electromagnetic response;

inverting the fourth electromagnetic response; and

inverting jointly the third and fourth electromagnetic responses.

21. The method of claim 20, wherein the step of processing the electromagnetic response further comprises at least one step chosen from:

inverting the first electromagnetic response;

inverting the second electromagnetic response; and

inverting the third electromagnetic response.

22. The method of claim 1, wherein the resistivity depth image comprises at least one depth image component chosen from an inverted vertical resistivity depth image, an inverted horizontal resistivity depth image and an inverted three-dimensional resistivity depth image.

23. The method of claim 1, wherein the dimensions and probing frequency are verified using iterated 3-D modeling.

24. The method of claim 8, further comprising continuously grounded linear terminating electrodes connected substantially orthogonally at each end of the grounded radial electrodes.

25. The method of claim 24, wherein the length of the terminating electrodes is less than or equal to one tenth of the length of the radial electrodes.

26. The method of claim 1, wherein the electromagnetic source comprises a sub-optimal configuration.

27. The method of claim 11, wherein the plurality of components of electromagnetic response comprise:

two orthogonal horizontal electric fields;

two orthogonal horizontal magnetic fields; and

a vertical magnetic field.

28. The method of claim 27, wherein the plurality of components of electromagnetic response further comprises a vertical electric field.

29. The method of claim 12, wherein the plurality of components of electromagnetic response comprise:

two orthogonal horizontal electric fields;

two orthogonal horizontal magnetic fields;

and a vertical electric field.

30. The method of claim 29, wherein the plurality of components of electromagnetic response further comprise a vertical magnetic field.

31. A method for surface estimation of an inverted resistivity depth image of a subsurface geologic formation, comprising the steps of:

determining the location of and average earth resistivity above, below, and horizontally adjacent to the subsurface geologic formation using geological and geophysical data from the vicinity of the subsurface geologic formation;

determining dimensions and probing frequency for an electromagnetic source to substantially maximize transmitted vertical and horizontal electric currents at the subsurface geologic formation using the location and the at least one average earth resistivity, said source comprising six or more grounded linear radial electrodes of equal lengths placed along radii separated by equal angles whose radial projections intersect at a common central point, continuously grounded linear terminating electrodes connected substantially orthogonally at each end of the grounded radial electrodes;

activating the electromagnetic source at or near the surface of the earth, approximately centered above the subsurface geologic formation;

measuring a plurality of components of electromagnetic response with a receiver array;

determining one or more geometrical and electrical parameter constraints, using the geological and geophysical data; and

processing the electromagnetic response using the geometrical and electrical parameter constraints to produce the inverted resistivity depth image.

32. A method for surface estimation of one or more properties of a subsurface geologic formation, comprising the steps of:

determining the location of and at least one average earth resistivity for the vicinity of the subsurface geologic formation using geological and geophysical data from the vicinity of the subsurface geologic formation;

determining dimensions and probing frequency for an electromagnetic source to substantially maximize transmitted vertical and horizontal electric currents at the subsurface geologic formation using the location and the at least one average earth resistivity, said source comprising six or more grounded linear radial electrodes of equal lengths placed along radii separated by equal angles whose radial projections intersect at a common central point;

activating the electromagnetic source at or near the surface of the earth, approximately centered above the subsurface geologic formation;

measuring a plurality of components of electromagnetic response with a receiver array;

determining one or more geometrical and electrical parameter constraints, using the geological and geophysical data;

processing the electromagnetic response using the geometrical and electrical parameter constraints to produce one or more inverted resistivity depth images of the subsurface geologic formation; and

combining the inverted resistivity depth images with the geological and geophysical data to estimate the properties.

33. A method for surface estimation of one or more properties of a subsurface geologic formation, comprising the steps of:

determining the location of and at least one average earth resistivity for the vicinity of the subsurface geologic formation;

determining dimensions and probing frequency for an electromagnetic source to substantially maximize transmitted vertical electric currents at the subsurface geologic formation using the location and the at least one average earth resistivity;

activating the electromagnetic source at or near the surface of the earth, approximately centered above the subsurface geologic formation;

measuring at least a vertical electromagnetic response with a receiver array;

determining one or more geometrical and electrical parameter constraints, using geological and geophysical data from the vicinity of the subsurface geologic formation;

processing the electromagnetic response using the geometrical and electrical parameter constraints to estimate the one or more properties.

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